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ABSTRACT

Owing to the proximity to seismically active faults as well as the population density in the band of Israel Seacoast between the towns of Ashqelon and Haifa, this region may be considered a high seismic risk zone. For quantitative assessment of seismic response in terms of horizontal-to-vertical (H/V) spectral ratios the ambient noise survey was carried out at 190 sites. Results derived from H/V analysis indicate site amplifications ranging from 1 to 8 within the frequency band 1.0-6.0 Hz.

The soil profiles at the investigated sites were very different. Some sites have simple profiles in the uppermost surface layer and clear seismic impedance between the soft soil layer and the bedrock. Other sites had complicated surface soil layers and a less distinct contrast between the surface soil and underlying bedrock. In many cases our attempts to estimate depth to the hardrock reflector from borehole data failed. Only when the distribution maps of the predominant frequency and the distribution of maximum amplification were constructed was the strong correlation between geological features and measurement results revealed.

The observed resonance frequencies and their amplifications were correlated with analytical functions that correspond to the 1-D subsurface model. Collection of available geological, geotechnical and geophysical data relevant to local geology and combination of the theoretical and experimental response functions provided reliable estimations of analytical site effects.

INTRODUCTION

The strong influence of near-surface geological conditions has been apparent from the damage distribution of many destructive earthquakes. Many methods have been used to characterize site amplification; the best approach being through direct observation of seismic ground motion, although such observations are limited to high seismicity areas and by their high cost. An alternative method, recording only one station, consists of dividing the spectrum of the horizontal component by that of the vertical component of ambient noise [Nakamura, 1989, 2000].

Most studies show that the H/V ratio obtained from microtremors coincides with response functions of near surface structures to incident shear wave [Lachet et al., 1996; Konno and Ohmachi, 1998; Chávez-García and Cuenca, 1998 and others]. Recently, Bonilla et al. [1997], Horike et al. [2001] and Satoh et al. [2001] contended that estimates of the frequency of the predominant peak are similar to those obtained from traditional sediment-to-bedrock spectral ratio of earthquake records, but the absolute level of site amplification does not correlate with the amplification obtained from earthquake data.

During the last decade, many sites in Israel have been investigated in an attempt to estimate the possible amplification of the seismic ground motion [Zaslavsky et al., 1995, Gitterman et al., 1996, Zaslavsky and Shapira, 2000, Zaslavsky et al., 2000, Shapira et al., 2001 and Zaslavsky et al., 2002a,b]. All these studies are based on analysis of ambient noise and weak motion measurements incorporated with geological and geophysical information about the subsurface. We used various empirical methods to determine the site response functions including reference and non-reference techniques and referring to different sources of excitation – earthquakes, explosions and ambient noise. Appropriate ensembles of carefully selected windows of ambient vibration provide estimations of site response that are similar to those obtained from the H/V spectral ratio of seismic events. There were, however, cases where the Nakamura technique failed to yield conclusive results. This often happens when the ratio of the shear-wave velocity of the soil to the shear wave velocity of the underlying half space (bedrock) is higher than 0.5-0.6 (amplification up to a factor of ~2) or when we are dealing with a complicated 3D structure of the underlying geology. Other examples are associated with poor excitation of the soil column due to weakness or remoteness of the microtremor sources.

The objective of this study included performing quantitative estimates of site effects using ground motion from ambient noise. An area of 850 square kilometers was analyzed using records from 190 sites. We prepared two maps that reflected the fundamental characteristics of site effects: distribution resonance frequency and maximum relative amplification. The observed resonance frequencies and their amplifications were correlated with analytical functions that correspond to the 1-D subsurface model. Combination of the theoretical and experimental response functions provided reliable estimations of analytical site effects. We used the adequate analytical transfer functions and Stochastic Evaluation of Earthquake Hazard to estimate Seismic Hazard in terms of ground motion parameters used for engineering purposes.

GEOLOGICAL SETTING

The investigated area is situated along the Coastal Plain extending from Ashqelon in the south to Haifa in the north and is about 140 km long and almost 8-10 km wide (see Fig. 1). The basic geological data collected from Gvirtzman (1984) and the new version of the geological map of Israel to a scale of 1:200,000 (Sneh et al., 1998) reveal the following geological units in the central part of the investigated area:

- the Quaternary sediments of Holocene age outcropping in the investigated area, represented by alluvium and sand dunes 0 to 30m thick;.
- the Kurkar Group of Pleistocene age consisting of alternating marine and Eolian calcareous sandstones, sands, red loam and conglomerates. The thickness of the Kurkar Group decreases from about 250m near the shoreline to 80m at a distance of 5-7 km from the coastline. The Kurkar Group unconformably overlies the clay of Pliocene age.

In the northern part of the investigated area, from Binyamina to Haifa (the Hof-HaCarmel area), the geological structure is considerably different. The Kurkar Gr., with a thickness of approximately 50 m near the coastline, wedges out eastward and overlays hard carbonates of the Turonian-Cenomanian age.

MICROTREMOR RECORDS AND DATA PROCESSING

Ambient noise measurements were carried out at 190 points in different lithological units in the coastal area between Ashqelon and Haifa. The distribution of the points for microtremor recording was based on the surface geological formation map. We planned 22 measurement lines from Ashqelon to Haifa. The distance between lines was approximately 5km. Most of the stations are located close to boreholes. The number of stations distributed along each line and the distance between them depended on the spatial distributions of the geological units and the availability of borehole data. Distribution of investigated sites is shown in Fig. 1.

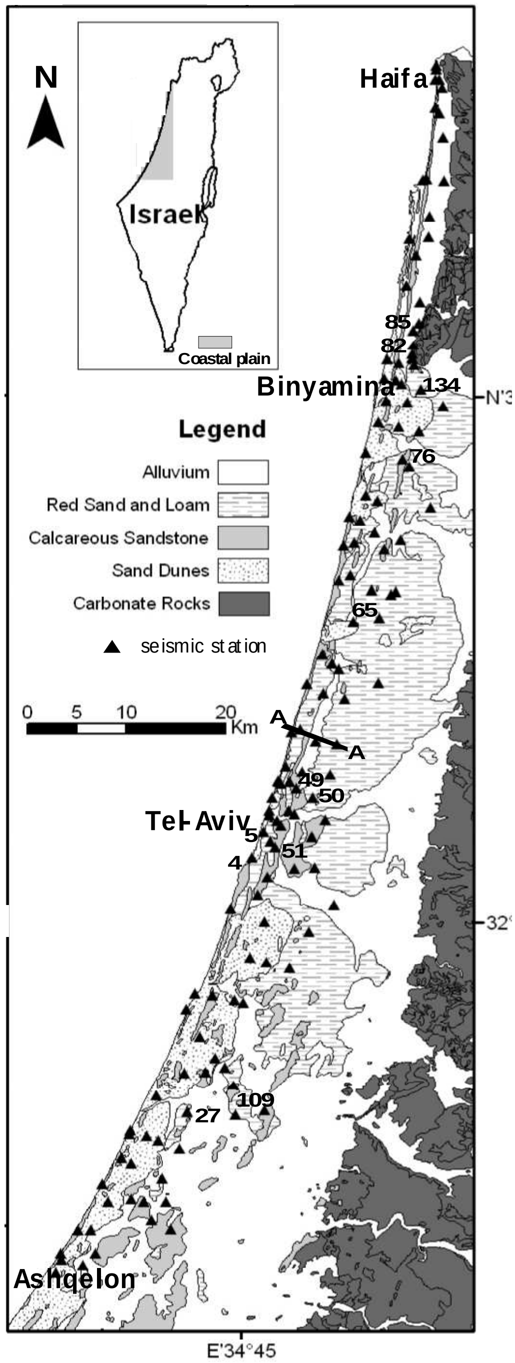

Fig.1. Geological map and location of the measurement points

The acquisition equipment included: 12-channel amplifier with a band pass filters 0.2-25 Hz, GPS (for timing) and a laptop computer with analog-to-digital conversion card. Digital recordings were made with a sampling rate of 100 samples per second. The recorder has 16-bit data word. Digital seismic data acquisition system designed for site response field investigations (Shapira and Avirav, 1995). The seismometers used were sensitive velocity transducers with a natural frequency of 1.0 Hz and damping at 70% of critical. Each of the stations was equipped with one vertical and two horizontal seismometers (oriented north-south and east-west). At each site, microtremors were recorded continuously for 1-1.5 hours, creating data files of 3 minutes each of microtremor data. All the equipment – sensors, power supply, amplifier, personal computer and connectors - were installed in the vehicle, which also served as a recording center. The selected time windows were Fourier transformed, using cosine-tapering (1 sec at each end) before transformation and then smoothed with a triangular moving Hanning window (0.5 Hz). The H/V spectral ratio was obtained by dividing the individual spectrum of each of the horizontal components [S_{NS}(f) and S_{EW}(f)] by the spectrum of the vertical component [(S_V(f)]. To obtain systematic and reliable results from the spectra of microtremors, we used several time windows that yielded a number of spectral ratios that, in turn, were averaged. We also experimented with computing the average of the spectral ratios and found the differences to be negligible.

RESULTS

The stability of results obtained from microtremors must be confirmed before interpretation of microtremor data. We studied (Zaslavsky and Shapira, 2000) the evolution of the H/V spectral ratios during different days and months and concluded that the dominant frequency and its amplitude are stable. Examples of the spectral ratios obtained at Point 4 from microtremors recorded in October 2001 and January 2002 are shown in Fig. 2. The shape of all average curves is similar. The dominant feature of the spectral ratios is a maximum at frequency 3.5Hz with an amplification factor of about 4.5.

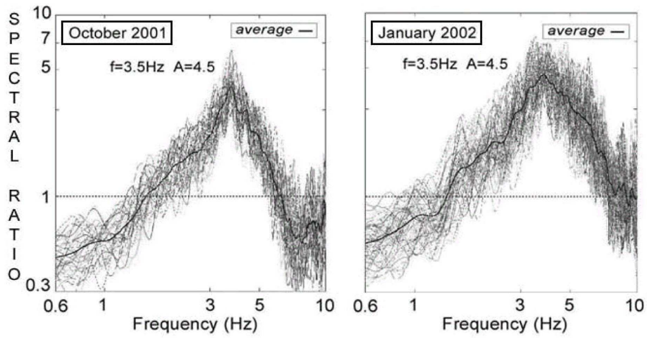

Fig. 2. H/V microtremor spectral ratios observed at Point 4 at different time.

Our observations revealed clear and consistent peaks of spectral ratios, which we could trace from site to site. Fig. 3a illustrates the characteristic average spectra of microtremors recorded at Point 65 and its H/V spectral ratios. An increase in the spectral levels of the horizontal components is clear in the frequency range from 2.5 to 3.0 Hz, while the spectrum of the vertical component is almost flat. Therefore, spectral ratios show a prominent peak at about 3.0 Hz with an amplification of about factor 3. In the second case (Fig. 3b), if we compare Point 51, we can see that in the vertical spectrum there is a narrow-bandwidth trough at the frequency near 1.5 Hz. Hence, the general character of the spectral ratios is clear amplification at a frequency of about 1.5 Hz. Fig. 3c reveals that the peak of the H/V ratio is localized by a narrow-bandwidth trough at frequency near 2.0 Hz in the vertical spectra as well as high in the horizontal spectra near 2.0Hz.

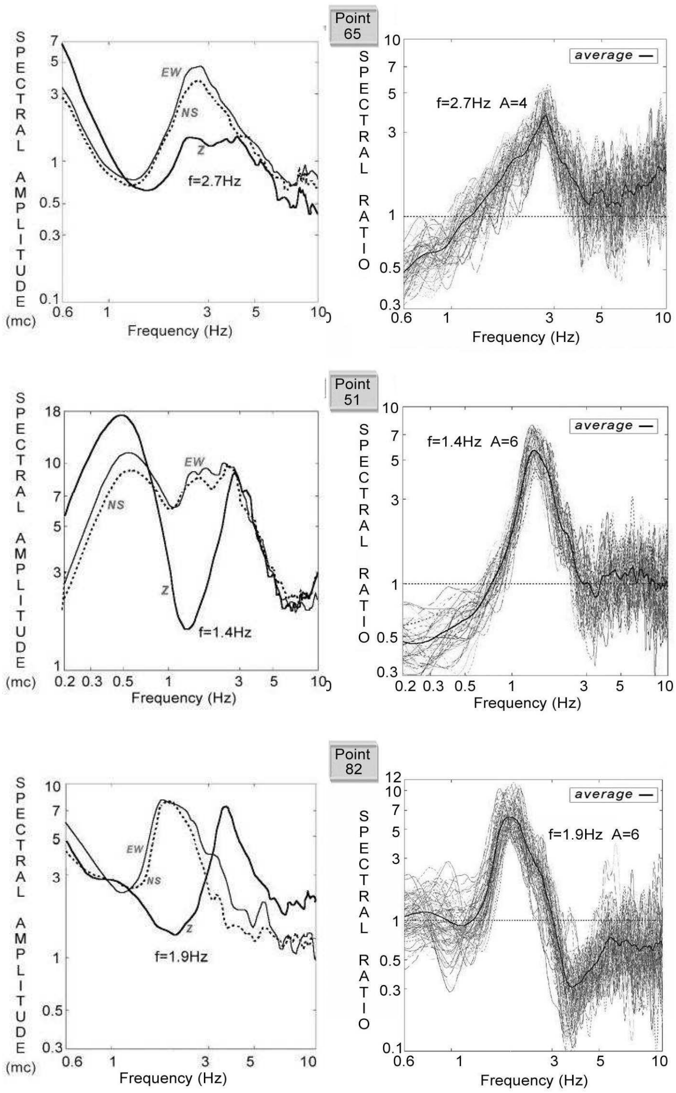

Fig. 3. Examples of average Fourier spectra and H/V spectral ratios in different sites providing true evaluation of site effects: (a) Point 65; (b) Point 51 and (c) Point 82.

In Fig. 4, we plotted the spectral ratios for the point located on calcareous sandstone. These figures demonstrate that the scatter between individual curves is high, but from the average functions of the spectral ratios it may be concluded that in the frequency range 0.6 Hz to 10 Hz, transfer functions are flat with unit amplification, i.e., there is no site effect.

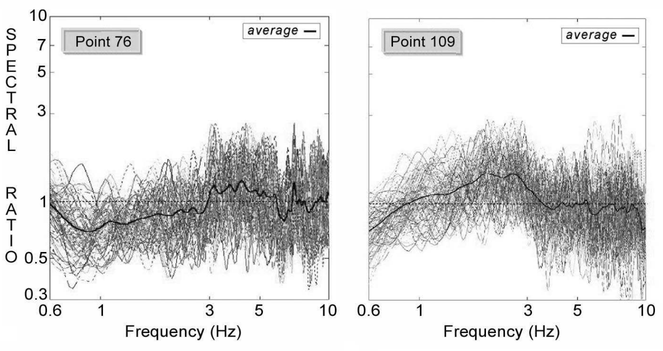

Fig. 4. Examples of individual and average H/V spectral ratios for points located on calcareous sandstone outcrop.

Microtremor H/V spectral ratios for Points 49 and 50 composed by unconsolidated sediments with thickness varying from 2 to 6m to bedrock are shown in Fig. 5. The bedrock consists of calcareous sandstone of the Kurkar Gr. These figures demonstrate similarity among the individual functions. The average spectral ratios (response functions) are flat in the frequency range 0.6 to 10 Hz. Consequently, these observations show that there are no site effect at Points 49 and 50.

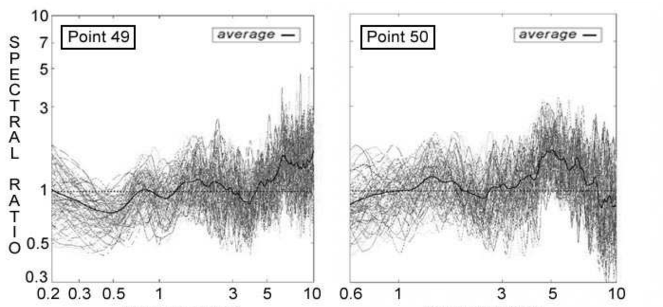

Fig. 5. Individual and average H/V spectral ratios for sites located on the thin (up to 6 m thick) unconsolidated sediments.

H/V ratios at Points 4, 27 and 134 are shown in Fig. 6. At these sites, the soil profile is very simple, namely "basement rock", consisting of calcareous sandstone underlying the soft layer represented by clay, sand and silt. As shown in Fig. 6a, the H/V ratio at Point 4 shows a very clear peak at frequency 3.3 Hz. On the other hand, at Point 134 the H/V does not show a well-defined peak at about 2 Hz. It should be noted that the S-wave velocity for calcareous sandstone is about 1100 m/sec, 900 m/sec and 700 m/sec at Points 4, 27 and 134, respectively. Using these examples we could illustrate that we obtain much clearer and more stable characteristics of H/V spectral ratios at points where a good S-wave velocity contrast, between the surface soft soil layer and the basement layer, is observed.

Fig. 7 shows observed horizontal-to-vertical spectral ratios obtained from ambient noise recorded at Points 85-1 and 85, which are only 150 m apart. These sites demonstrate the great variability in site response over very short distances. Spectral ratios for Site 85 are flat with no amplification while the average spectral ratio of Site 85-1 shows a prominent peak at 1.2 Hz with amplification factor up to 8.

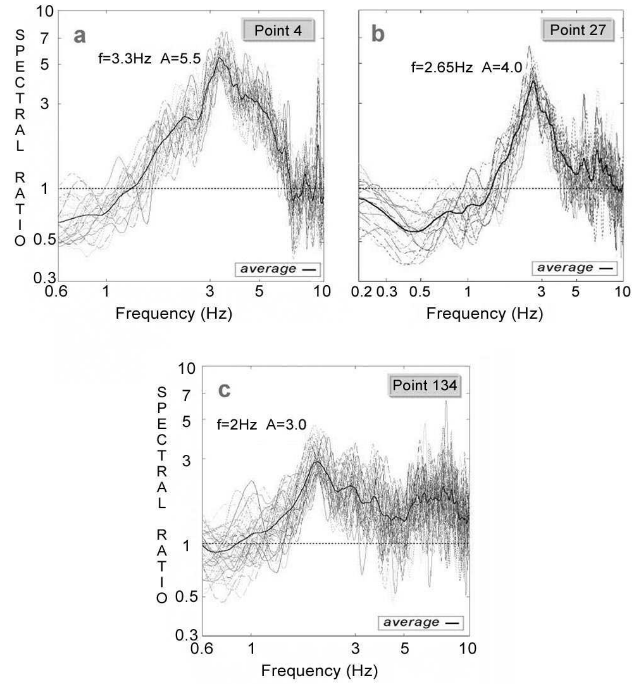

Fig. 6. H/V spectral ratios for points located on the identical soil profile: soft sediments overlay calcareous sandstone with different S-wave velocities: (a) Vs=1100 m/sec; (b) 900 m/sec and (c) 700 m/sec.

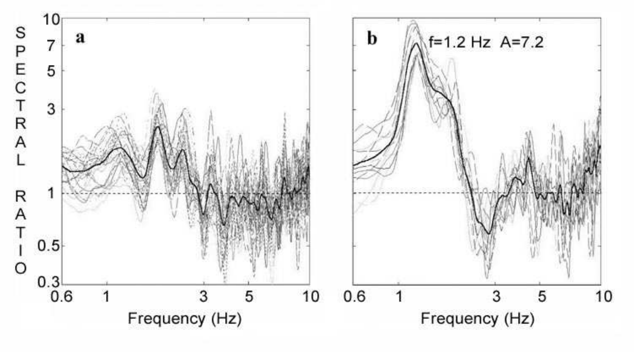

Fig.7. Example of significant variation of site effect over very short distance: (a) Point 85 and (b) 85-1.

After processing of each record to obtain parameters of site response, the maps of the fundamental frequency and maximum relative amplification factor were produced to show its spatial variation over the region of interest (Fig. 8a,b). In the southern part of the area (from Ashqelon to Binyamina) dominant frequencies reach 3 Hz on the sand along the beach and decrease to the west up to 1.0 Hz, correlated well with the thickness of the sedimentary deposits. In the northern part of the area (from Binyamina to Haifa) the sediments present a predominant frequency of 2-6 Hz suggesting that the sedimentary cover is rather thin. Amplification map of the Coastal Plain reveals two geographical zones differentiated by their amplification values. In the southern part, sand dunes and alluvium sediments of Holocene age over the Kurkar Group, do not show a strong contrast. Therefore, most of sites examined are associated with amplification factors between 2-3 and only some sites reveal amplifications between factors 3-6. In the northern part, silts, clays, loose sands, and loam of the Kurkar Group over the Turonian-Cenomanian carbonates show a strong contrast and cause amplification factor up to 7.

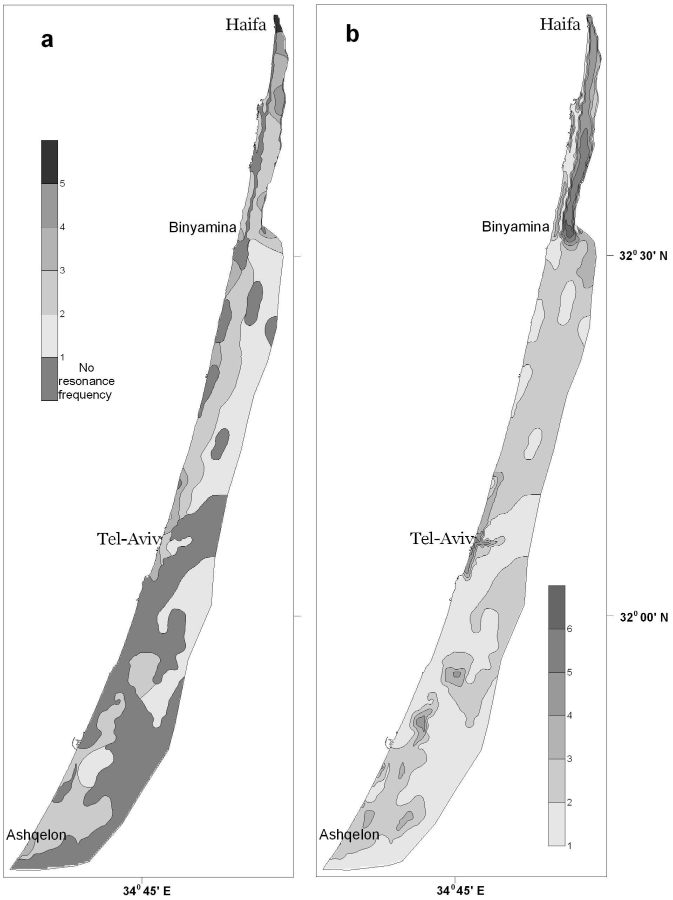

Fig. 8. Distribution of the fundamental frequency (a) and maximum amplification factor (b) for the Coastal plain area

ONE-DIMENSIONAL MODELING

In order to obtain a more general representation of the site response function by implementing modeling technique, we computed one-dimensional models. For the theoretical transfer functions calculations we used the Joyner (1977) and SHAKE (1971) programs. These programs require detailed knowledge of the thickness, density and shear-wave velocity of each layer of a multi-layered medium. In order to collect additional information about layers thickness, more than 230 oil and gas boreholes were inspected. Our attempts to use information from the map of sediment thickness at the Coastal Plain (Kravtsov at al., 1997) as well results of interpretation of seismic refraction surveys carried out along the coastline (Shtivelman, 1999) did not yield satisfactory results. The shear-wave structures for different layers were deduced by trial-and-error fitting of observed and theoretical transfer function. Fig. 9 shows the comparison of analytical and empirical response functions at Point 123 (Yehoshua well) together with the corresponding lithological cross-section.

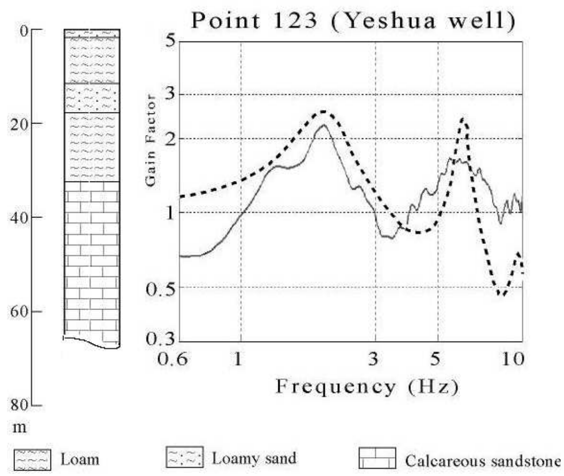

Fig. 9. Comparison between analytical and experimental response functions for Point 123

For the initial range of S-wave velocity values for model development, we took the results of refraction surveys obtained in different areas of Israel. In Table 1 we present a three-layer model for Point 123 derived by trial-and-error procedure of adjusting the analytical response functions to empirical one.

Suggested S-wave velocities yield a satisfactory agreement between fundamental resonant frequency and maximum amplification of the model and experimental function.

Table 1. Geotechnical models used in theoretical site response estimate and comparison between fundamental parameters of experimental and calculated response functions for Point 123

Material	Loamy sand	Loam	Loamy sand	Calcareous sandstone
Thickness, m	12	6	15	Half-space
Vs range by refraction surveys, m/sec	190-300	280-370	190-300	360-1100
Optimal Vs model, m/sec	250	350	250	700
Fundamental frequency	observed		1.9	
	calculated		1.9	
Amplification factor	observed		2.3	
	calculated		2.6	

The fitting procedure was repeated, retaining velocity values derived from modeling at Point 123, for some other sites situated close boreholes. Fig. 10 displays such an example for Point 58. S-wave velocities for loam and calcerous sandstone are taken from the model described above, while, for the layer of sand, we fitted a value of 200 m/s.

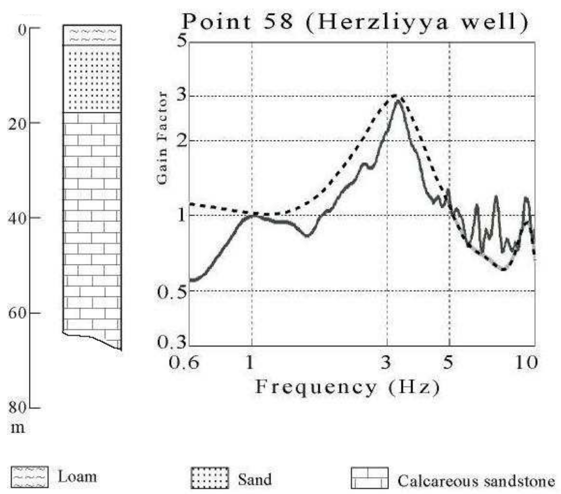

Fig. 10. Comparison between the experimental and analytical response functions for Point 58

For the Carmel coastal area, where the loose sediments overlaying chalk and dolomite can yeld high level of amplifications, the shear-wave structures for different sediments and rocks (reflector) deduced by trial-and error fitting of observed and theoretical transfer functions are summarized in Table 2.

Table 2. Optimal S-wave velocity models used in theoretical site response estimation

Material	Vs, m/sec
Silt	180
Sand	200
Loamy sand	250
Loam	350
Sandstone	700
Chalk	1000
Dolomite	1600

PREDICTION OF GROUND MOTION

In recent years, considerable research has been focused on establishing reliable methods to predict earthquake ground motion for seismic hazard assessment. In this study we used the adequate analytical transfer functions and Stochastic Evaluation of Earthquake Hazard (SEEH) method (Shapira and van Eck, 1993) to predict the Seismic Ground Motion Hazard in terms appropriate for engineering purposes: site specific acceleration response spectra computed for 10% probability of exceedence during an exposure time of 50 years and for a damping ratio of 5%.

The SEEH computations require information about several seismological parameters such as distribution of seismogenic zones, stress drop, Q-values, seismic moment – magnitude relationships, etc. Estimations of these parameters are based on seismological data (local and regional earthquakes) provided by the Israel Seismic Network. The SEEH is based on seismicity simulations, synthetic ground motions and Monte-Carlo statistics. The SEEH also incorporates the uncertainties associated with almost every parameter needed in the computations. Synthetic accelerations for hard rocks are convolved with the site-specific response function of the investigated site to yield the acceleration spectrum on a damped oscillating system (i.e., the acceleration response spectrum). We used 70 and 35 analytical response functions for the southern and northern zones of the Israel Coastal plain, respectively. The results of our computations are shown in Fig. 11. We also plotted the acceleration response spectra corresponding to the current Israel Standard (IS-413) for the central and Carmel coastal areas tied to the horizontal PGA value of 0.1g and 0.15g respectively. The shape of the spectra obtained for the two zones are significantly different from that prescribed by IS-413, in that IS-413 underestimates in the period from 1 sec to 0.2 sec.

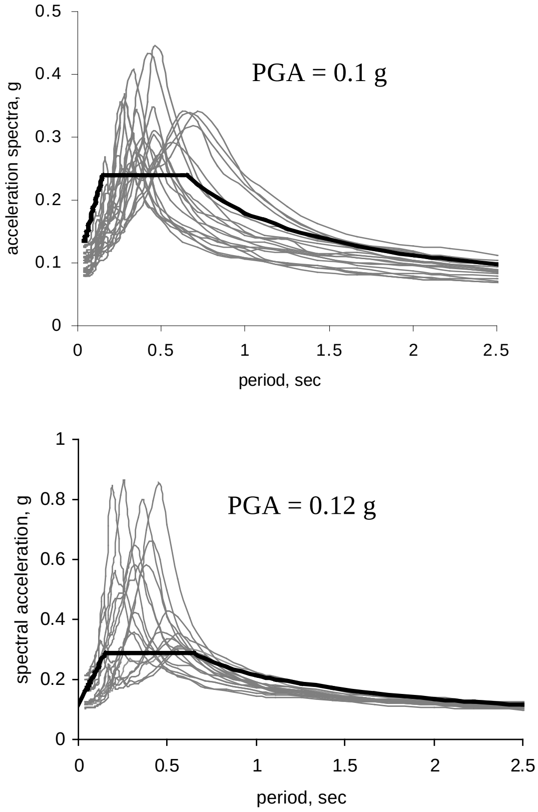

Fig. 11. Comparison of 5% damped site-specific acceleration spectra obtained by SEEH method (thin lines) and design spectra of Israel Standard (IS-413) for two zones of Coastal plain (heavy line) with different Peak Ground Acceleration (PGA)

DISCUSSION

After the occurrence of recent earthquakes, a priori estimations of site effects have become a major challenge for efficient mitigation of seismic risk because, in the case of moderate earthquakes, significant damage and loss of life has been directly related to local geotechnical conditions. In situ measurements with controlled-source seismic methods allow us to image the subsurface structure. However, it is, in general, not possible to carry out such measurements in regions where the seismic activity is relatively low, as in Israel. We therefore focused on ambient noise measurements. The practical relevance of investigations in the Coastal plain area is illustrated on the geological cross-section located north of the Tel-Aviv area (Fig. 12). An increase in sedimentary thickness from 5-10m at the shoreline up to 50-70m to the east is detected by the measurements, namely, by a dominant frequency decreasing from 3.4 Hz at Point 58 up to 1.6 Hz at Point 60. Higher amplifications up to factor 4-5 were observed at the Yarkon riverbed and could be explained by a consolidation of sandstone along the riverbed and its facies substitution by limestone. Using results of ambient noise analysis we established that in the central region of the

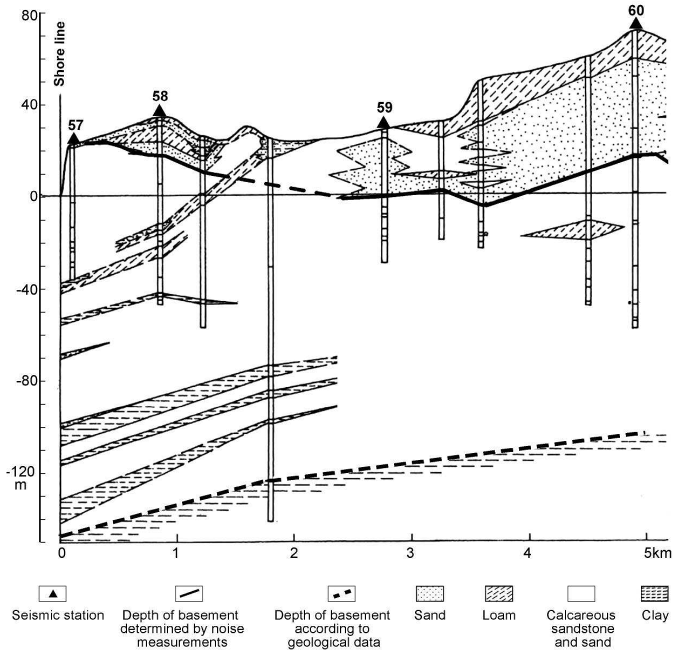

Fig.12. Geological cross section in the north of the Tel-Aviv area (line A-A in Fig.1)

investigated area (Ashqelon-Binyamina) the reflector (half-space) is calcareous sandstone of the Kurkar Group, but not clay of the Yaffo Fm. as was assumed anteriorly according to geological information.

In the Carmel coastal zone, distinguished on the amplification map owing to its higher level of amplification values, reflector (half-space) is correlated to the hard carbonates of the Judea Group. According to our observations, maximum amplifications up to factor 7 are observed in areas where 15-35 m thick silt together with calcareous sandstone overlays dense dolomites and chalks. The prevalent frequency in Carmel coastal area is 2-3 Hz. The increase in dominant frequency to the north is related to the thinning of the sedimentary cover and/or the lithological composition of sediments.

Generally speaking, theoretical site response estimation requires local information on spatial distribution of the soft materials above the hard bedrock in terms of densities and shear-wave velocities or equivalent parameters. In many cases the complexity of actual conditions and the uncertainties associated with interpreting indirect measurements, limit the availability, quality and reliability of these data. Hence, different possible models of the subsurface based on the same geological and geophysical observations may yield analytical functions that are very different from those obtained empirically. As demonstrated in Fig. 13, there is a difference between the theoretical transfer function derived on the basis of available information about subsurface structure at Point 59 and the response function obtained from measurement data.

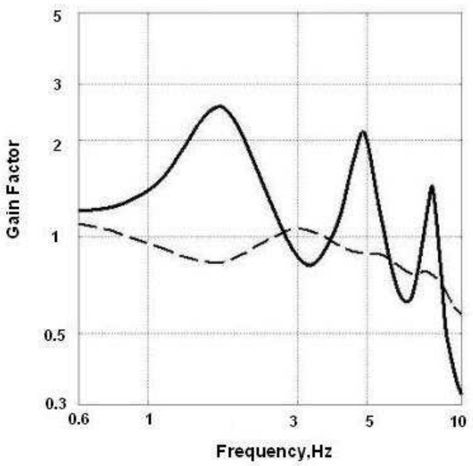

Fig. 13. Difference between analytical response functions for Point 59 calculated on the basis of geological (dashed line) and measurement data (solid line)

CONCLUSIONS

The experiment discussed in the present study had the following goals:

- in situ site effect estimations in the Coastal Plain area between Ashqelon and Haifa using the microtremor measurements of ground motions;
- improving theoretical site response determinations by comparing the empirical and the analytical assessments, selecting parameters of soil column models for satisfactorily predicting the transfer function by multi-layer 1-D models when linear behavior of the soil is assumed;
- evaluating site-dependent seismic hazard in terms of ground motion parameters used for engineering applications.

The conclusions may be summarized as follows:

1. The soil profiles at the investigated sites are very different. Only when the distribution of the predominant frequency and maximum amplifications maps were constructed, was the strong correlation between features of geological structure and measurement results revealed.

2. The joint application of analytical and empirical techniques for assessing soil response functions can provide useful feedback to improve the reliability of the results obtained. A detailed comparison of the analytical and empirical values constitutes a low-cost, efficient and fast procedure to establish the spatial dependence of both suitability and reliability of the method, improvement of models assumed are needed for proper assessment of soil response.

3. Ambient noise studies with horizontal-to-vertical spectral ratio can yield information relevant to the field of earthquake hazard assessment and microzonation. This is especially true given the lack of alternative economical and time-saving methods available for characterizing site response in regions with low levels of seismicity.

4. The hazard assessment presented here in terms of Uniform Site Specific Acceleration Response Spectra may be useful for land-use planning or for making regional hazard mitigation decisions. The use of these maps in loss estimation can help the respective authorities to set priorities in enforcing building codes, conducting seismic strengthening programs for existing structures, and in contingency planning for emergency response and long term recovery.

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